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Assessing Stand-Level Climate Change Risk Using Forest Inventory Data and Species Distribution Models

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Climate change is having important effects on forest ecosystems, presenting a challenge for natural resource professionals to reduce climate-associated impacts while still achieving diverse management objectives. Regional projections of climate change and forest response are becoming more readily available, but managers are still searching for practical ways to apply this information. We propose that commonly collected forest inventory data be used in conjunction with species distribution models to better understand the potential response of forests to climate change and inform management at the site level. In this article, we propose a new climate risk metric that incorporates stand-level forest inventory data with projections of tree species habitat from the Climate Change Tree Atlas. This climate risk metric can serve as a starting point for managers to consider how forests may be altered by climate change. We also describe two examples of how this metric was used in real-world management situations.

Keywords: adaptation, climate change, management, measurement

Forest and natural resource managers are rapidly making strides to incorporate climate change considerations into forest management planning and activities, with a diverse set of actions being implemented to enable forests to adapt to changing conditions (Swanston et al. 2016, Janowiak et al. 2014b, Stein et al. 2014). As managers increasingly pursue actions that respond to changing conditions or anticipate potential future conditions, they will need to bx-become more agile to incorporate new information and learn from other failures and successes (Swanston et al. 2016). Within this context, there is active discussion about the use of monitoring and evaluation to assess the success of management projects—particularly those claiming adaptation benefits—and inform future management actions (Peterson et al. 2011, Stein et al. 2014, Rowland and Cross 2015). Likewise, adaptive management principles are often suggested for use in climate change adaptation because of its emphasis on monitoring and continued learning for impacts in which there is a high degree of uncertainty (Holling 1973, Joyce et al. 2008).

Although there is value in thinking broadly about climate change monitoring, many forest managers are asking the more pragmatic question: *How can we assess climate change risk with the least amount of additional work (or cost)?* Within this context, traditional forest inventory data will be increasingly important for understanding how forests are responding to change in climate, as well as informing management options and responses. By describing the current condition of the forest, inventory data can help identify how forests are responding to a changing climate. Further, when used over time, inventory data can also be used to eval-

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This article uses metric units; the applicable conversion factors are: kilometers (km): 1 km = 0.621 mi.

uate whether management actions are reducing risk and enabling ecosystems to adapt favorably to future conditions. By leveraging data that are already available, climate change considerations can be fully integrated into existing management plans and practices, rather than creating a new, separate data collection approach. In this article, we propose a new climate risk metric that integrates commonly collected, stand-level forest inventory data with projections of tree species habitat under scenarios of climate change to help inform management decisions.

The forest inventory is a fundamental part of forest management used to quantify attributes of a forested area to support decisionmaking (Helms 1998, Avery and Burkhart 2015), and inventory data are commonly collected and used by diverse forest management organizations for many types of projects. Although forest inventories vary widely depending on the type and precision of information needed, as well as time and money available to conduct the inventory, most forest inventories collect measurements of tree species and size (e.g., diameter) as core components for characterizing stand attributes. At the stand or management unit level, the forest inventory helps describe the current condition of the forest to provide a basis for making management decisions as well as establishing a reference point for evaluating forest change over time.

Data describing potential responses of species to climate change can be a valuable addition to existing inventory data when considering how a stand may respond to climate change. Modeled projections of future species habitat are increasingly available and of interest to managers, although there are few direct ways that this information is currently being applied in management. Species distribution models examine the features that contribute to a tree species' current habitat and then project where similar habitat conditions are likely to occur in the future (Pearson and Dawson 2003, Schneiderman et al. 2015). These models project changes in the distribution of individual species, allow for unique responses from individual species, and acknowledge the potential for novel species assemblages in the future (Iverson et al. 2008). Despite their limitations, these relatively simple models represent one of the best tools available to inform decisionmaking (Hannah et al. 2002, Pearson and Dawson 2003, Wiens et al. 2009).

Because future climate data are necessarily modeled at regional and global spatial scales and US Department of Agriculture Forest Service (USDA) Forest Inventory and Analysis (FIA) plots are widely spaced, adequate projections of responses of tree species to climate change are most relevant at the regional or ecoregional level; however, management is generally implemented at the stand level. Combining coarse-level models of potential changes in tree species habitat with traditional forest inventory data bridges this divide by allowing managers to assess the overall tendencies for forest habitat change from a changing climate at the stand or management unit level. This approach does not assume that regionally derived data projecting forest change will be equally applicable across the landscape; rather, it highlights regional trends to managers, who can then interpret this information in the context of particular management objectives and their evaluation of site-specific climate change vulnerabilities.

The Climate Risk Metric

Data on projected changes in tree species habitat from the Climate Change Tree Atlas were used to develop a climate risk metric (Iverson et al. 2008, Landscape Change Research Group 2015). The Tree Atlas presents models of potential changes in suitable habitat, at a scale of 20 × 20 km across the eastern United States, for 134 tree species out to the end of this century[1]. These models were generated using FIA-based estimates of importance value, based equally on basal area and number of trees on each plot, along with 38 environmental variables to create suitable habitat (importance value) models for each 20 × 20 km cell for the species in the eastern United States, using the RandomForest statistical modeling tools (Prasad et al. 2006). Model outputs of current distribution were also compared with FIA data, and several metrics were used to generate a reliability score for each model (Iverson et al. 2008). Outputs of suitable habitat for each species under two scenarios of climate change were created for the period 2070–2099 as part of a series of vulnerability assessments developed for forested areas of the midwestern and northeastern United States.[2] Model outputs are summarized for the study area of interest, ranging from state, county, ecoregion, and so on, but a minimum of 40 12.4 × 12.4 mi (20 × 20 km) cells are necessary to pool variability and minimize model artifacts. The model outputs were intended to indicate nearly the full range ("bookends") of potential changes in suitable habitat for tree species that may eventually occur under climate change: a "low" change scenario using the Parallel Climate Model (PCM) (Washington et al. 2000), a model of less sensitivity to atmospheric greenhouse gas concentrations, paired with an optimistic emissions scenario projecting a reduction in human greenhouse gas emissions early in this century (the B1 scenario) (Nakicenovic and Swart 2000); and a "high" change scenario with the Geophysical Fluid Dynamics Laboratory (GFDL) model (Delworth et al. 2006), a model with more sensitivity, coupled with an emissions scenario that is more similar to our current trajectory of emissions (the A1FI scenario) (Peters et al. 2013).

Area-weighted importance values were then used to identify species that are at risk of decline as a result of climate change. Based on ratios of projected future suitable habitat to current habitat, species were ranked into these classes: large decrease, small decrease, no change, small increase,

Management and Policy Implications

The forests of today, and the ecosystem services they provide, will continue to undergo changes as a result of direct (e.g., temperature and precipitation) and indirect (e.g., pests and pathogens) effects of climate change. Forest and natural resource managers are increasingly looking for actions that enhance forest resilience and improve the ability of forests to adapt. By integrating climate change information into existing forest inventory data sets and protocols, managers will be better able to make science-based decisions regarding possible interventions for climate change adaptation. The combined consideration of management goals, landscape context, site conditions, and climate change vulnerability under different scenarios of climate change will help identify opportunities to suit a range of management needs. These opportunities could range widely depending on management goals and constraints, such as protecting species through climate refugia, promoting diversity to reduce risk, or facilitating changes in species composition via corridor promotion or assisted migration.

Table 1. Description of change classes used for Climate Change Tree Atlas data based upon the ratio of future projected area-weighted importance values to current modeled importance values.

	Future/current modeled importance value	
Change class	Common species	Rare species
Large decrease	<0.5	<0.2
Decrease	0.5–0.8	0.2–0.6
No change	>0.8–<1.2	>0.6–<4
Increase	1.2–2.0	4–8
Large increase	>2	>8

Species were considered rare if the current modeled importance value is less than 10% of the number of pixels in the analysis area. Species projected to have a decrease or large decrease in future habitat are considered to be at risk of decline from climate change.

large increase, new species habitat under both scenarios, or new habitat only under the high scenario (Table 1) (Brandt et al. 2014, Janowiak et al. 2014a). For this application, we identified species as being at risk of decline when they were projected to have 20% or greater decrease in suitable habitat by the end of the century in the region that was selected for analysis. Species that are projected to have a large decrease in suitable habitat (suitable habitat is expected to decrease 50% or more) may be at an even greater risk of decline. This does not mean that at-risk species are expected to immediately die or disappear; rather, this indicates that overall habitat suitability for a species is projected to decrease by the end of the century across a relatively large region.

The at-risk species data from the Tree Atlas were then combined with stand inventory data to evaluate the potential for climate change-related declines within an individual stand. This is done by calculating the relative dominance of each species within a stand in terms of importance value. Then, the proportion of the stand made up of individual at-risk species (i.e., projected decreases in suitable habitat of 20% or more by 2100) is summed to provide a stand-level value of risk for each climate change scenario (Table 2). This value ranges from 0%, at which no species are projected to lose suitable habitat, to 100%, at which the entire stand or unit is composed of species expected to have reduced habitat suitability at the end of the century. This calculation is performed separately for each of the two climate scenarios to illustrate a range of potential outcomes.

Application of the Climate Risk Metric

The climate change risk metric provides a simplified "gateway" that allows managers to begin using the substantial set of information available through the Tree Atlas. The emphasis on the risk of decline is appropriate because it identifies the potential to lose what is currently present in a stand, which is a necessary first step in exploring how forest change may unfold at a particular place. For natural resource professionals who are tasked with managing the existing forest to meet diverse needs, identifying the components of the current stand that may be at risk is helpful for gathering a sense of how much change may occur in the future and, therefore, to what degree management strategies and actions need to account for potential changes.

Although some species will be at risk of decline because of climate change, the Tree Atlas also identifies species that may have increased or new suitable habitat in the future. Consideration of these species is also important for informing management actions, especially in conjunction with evaluation of potential replacements for species projected to decline substantially in habitat. In this regard, a high risk value could signal the need to evaluate how the other species may respond and whether any species projected to have increased habitat should be favored. Potential increases in habitat are important to consider, but the climate risk metric presented here focuses on those at risk for decline as it is of more immediate concern for management and it carries less uncertainty with respect to future conditions. For example, tree species that are currently present in a stand and projected to increase may not be able to take advantage of more favorable climate conditions until additional growing space becomes available through management or disturbance; it is also uncertain whether species that are not currently present will be able to establish and grow on a particular site, even with the potential for increased habitat.

It is also important to recognize that the modeled outputs are necessarily general, or regional, in nature. The proportion of the stand that is at risk of decline is a starting point for further consideration of regional climate trends and their local implications for management. More specifically, managers may want to answer one or all of the following questions, discussed below, in considering how to respond to the risk value:

- How are specific tree species projected to respond to climate change and why?
- How might these changes play out within the context of a particular landscape and stand?
- What is an acceptable level of risk?

How Are Specific Tree Species Projected to Respond to Climate Change and Why?

The risk metric intentionally provides a simplistic indicator of climate change projections, intended to pique interest and encourage further consideration of the robust set of information available through the Tree Atlas, ecoregional and regional vulnerability assessments, and other sources that describe forest response to climate change. Beyond the risk metric, the Tree Atlas provides information on tree species that are projected to have increased and new habitat suitability, which may highlight opportunities to favor future-adapted species within management that would not have been considered otherwise. The Tree Atlas also includes a summary of modification factors based on species' life history traits to better interpret how a given species might respond to climate change (Matthews et al. 2011). These should be also evaluated before management decisions for particular species are made. Multiple literature sources are used to rate 9 biological and 12 disturbance characteristics for their positive or negative impacts on the species' capacity to cope with the many changes (for example, more disturbance impacts, like floods, droughts, and pests in the future) associated with climate change (Matthews et al. 2011). These values provide additional information that managers are encouraged to consider and modify based on local knowledge and site conditions or to revise based on an updated and more comprehensive literature review. The values can then be used to qualitatively modify, up or down, the projections of the empirically derived model outputs used in the risk metrics. Further, published vulnerability assessments are available for many areas and provide valuable information about regional climate change impacts on forests, including additional information on how individual species and ecosystems are expected to change (Glick et al. 2011, Peterson et al. 2011).

Table 2. Example of the calculation of the proportion of a forest stand that is at-risk under a low (PCM B1) and high (GFDL A1FI) climate change scenario.

				Low change (PCM B1)			High change (GFDL A1FI)		
Species	Tree atlas model reliability	Basal area	Importance value (%)	Future/current habitat	Change class	At-risk proportion of stand (%)	Future/current habitat	Change class	At-risk proportion of stand (%)
American basswood	Medium	18.5	12.3	1.1	No change	0.0	1.4	Increase	0.0
Bigtooth aspen	High	10.0	5.5	1.0	No change	0.0	0.4	Large decrease	5.5
Bitternut hickory	Low	0.4	2.4	2.3	Large increase	0.0	3.2	Large increase	0.0
Black ash	High	1.5	1.2	0.7	Decrease	1.2	0.6	Decrease	1.2
Black cherry	High	0.4	1.1	2.4	Large increase	0.0	1.4	Increase	0.0
Eastern hemlock	High	1.2	0.8	1.2	Increase	0.0	0.4	Large decrease	0.8
Northern red oak	High	1.5	3.2	1.3	Increase	0.0	1.1	No change	0.0
Paper birch	High	1.9	2.0	0.7	Decrease	2.0	0.2	Large decrease	2.0
Quaking aspen	High	0.8	0.8	0.6	Decrease	0.8	0.2	Large decrease	0.8
Red maple	High	4.2	5.0	1.0	No change	0.0	0.6	Decrease	5.0
Sugar maple	High	79.0	40.8	0.8	No change	0.0	0.3	Large decrease	40.8
White ash	High	33.1	17.9	1.6	Increase	0.0	1.9	Increase	0.0
Yellow birch	High	7.7	7.0	0.8	Decrease	7.0	0.2	Large decrease	7.0
Total		160.2	100.0			11.0			63.1

Risk was assessed for a stand in northern Wisconsin using forest inventory data for overstory trees (>4.5 in. dbh). Projections for the Climate Change Tree Atlas were used to identify tree species that are expected to have a 20% or greater decrease in suitable habitat (Table 1), putting them at greater risk. Overstory tree data in this example are from the State Ice Age Trail Area in Lincoln County, Wisconsin.

How Might These Changes Play Out within the Context of a Particular Landscape and Stand?

The relatively broad-scale habitat projections from the Tree Atlas are intended to be interpreted within the context of the local landscape and the attributes of a particular site. Managers are encouraged to approach the model results with productive skepticism to identify factors on the landscape that may influence outcomes at a particular location. When using the climate risk metric, a species is likely to be at greatest risk of decline when the available information (e.g., Tree Atlas, modification factors, or regional assessments) indicate the likelihood of reduced habitat suitability and that information is consistent with a professional's informed assessment of site-level risk. For example, a species that is projected to have a 50% decrease in suitable habitat by the end of the century is also projected to maintain 50% of its suitable habitat: although these values may be true across the region, professional judgment, expertise, and familiarity with current and past (i.e., changing) local conditions are needed to evaluate how much a species is at risk in a particular location. Site conditions, past management history, current management, disturbance history, projected trends in disturbance, and other factors will influence how regional projections of habitat change translate to local changes in tree species composition and health. In particular, the unique attributes of a stand in relationship to the broader landscape—factors such as soils, slope, aspect, and elevation—will have important influences on stand dynamics over time, and the presence of microsite variation or unique biophysical characteristics may warrant special consideration of potential resilience among tree species and forest communities (Anderson and Ferree 2010, Fridley et al. 2011). It is at the discretion of the manager to determine how the potential impacts to a particular site will influence the management of that location.

Importantly, repeated use of the climate-informed metrics for the same management area can be used to evaluate changes over time, as well as indicate the likely effectiveness of management actions for adaptation. For example, repeated use of the climate risk metrics could give an indication of whether management is altering forest composition in a way that reduces the dominance of tree species that are projected to have reduced suitable habitat. Where initial conditions point to a high proportion of tree species that are susceptible to climate change (i.e., high risk), a manager could look to the metrics for evidence of a reduction in the abundance of at-risk species as a signal of potentially lowered forest risk.

What Is an Acceptable Level of Risk?

Lastly, it is important to recognize that risk is likely to be perceived and evaluated differently by managers based on their individual management philosophy, as well as that of the landowner and management organization for whom they are working. There is not a particular threshold for species richness or climate risk that will guarantee resilience to climate change. Instead, a more realistic goal is to generally move in the desired direction over time (e.g., increase diversity, increase regeneration of future-adapted species, or shift species composition away from at-risk species) in a way that also supports the management goals of a particular area. Akin to personal investment portfolios, landowners, managers, and management organizations may each have a different "risk tolerance" informed by their management goals, available resources, and time horizons. For example, risk may be perceived differently where management goals dictate the future presence of particular species that have the potential to decrease versus situations where a specific forest composition may be less important.

Examples of the Climate Risk Metric

We used the climate change risk metric to assess the potential for forest change for two forested properties in northern Wisconsin that are part of a network of more than 200 climate change adaptation demonstrations developed through the Climate Change Response Framework.[3] Climate change information, including the climate risk metric, informed the development of forest management plans for each property that explicitly considered climate change. Each application is summarized briefly below and examples of stand-level climate change reports incorporating the two metrics are available in Supplemental Reports S1 and S2.S

Ice Age Trail Property

The Ice Age Trail (IAT) is a National Scenic Trail, located entirely within Wisconsin, which travels through 30 counties on state, federal, county, and private lands. Managed by a partnership among the National Park Service, the Wisconsin Department of Natural Resources, and the Ice Age Trail Alliance, the IAT is used primarily for off-road hiking and backpacking and provides excellent opportunities for sightseeing, wildlife viewing, and bird watching. State Ice Age Trail Areas (SIATAs) are owned and managed by The State of Wisconsin to permanently protect segments of the IAT, preserve Wisconsin's glacial landscape features and other natural and cultural resources, and, where possible, offer primitive and remote opportunities for visitors to experience a quiet connection with nature. The desired condition of the SIATAs is for high-quality, resilient natural communities. In the development of property management plans, the specific characteristics of each SIATA are considered, including the vegetation that existed before European colonization, existing vegetation, soil types, landscape position, and context as well as feasibility of the Department and its partners to maintain the natural community types.

Within this context, one 39-acre northern hardwood stand within the SIATA property in Lincoln County was assessed for management options to help assist with management planning (see Supplemental Figure S1). A portion of this assessment dealt with consideration of potential climate change impacts and associated risks. The Wisconsin Department of Natural Resources performed a complete forest inventory of the stand during the fall of 2015. This forest inventory was managed and processed using NED-3, a forest ecosystem management decision support system developed by the USDA Forest Service.[4] NED-3 is part of a suite of software products intended to help foresters and other resource managers develop goals, assess current and future conditions, and produce sustainable management plans for forest properties. The NED-3 program was used to calculate and summarize climate risk for the existing stand and highlight species projected to have reduced or new habitat by the end of the century. Data are presented for two contrasting climate change scenarios (PCM B1 and GFDL A1FI) to demonstrate a potential *range* of change that may be expected by the end of the century (see Supplemental Report S1).

The climate risk metric was applied to three size classes of trees: overstory trees (>4.5 in. dbh), established regeneration (1.0–4.5 in. dbh), and seedlings (<1 in. dbh but >6 in. tall).

In this stand, representative of the northern hardwood type in the local area, the risk of species decline was much lower under the scenario projecting less severe climate change (PCM B1), where 11% of the species present in the stand were projected to decline by the end of the century (Table 2). This was in contrast to the high change scenario (GFDL A1FI), where 63% of the overstory was identified as at risk as several species are expected to undergo greater declines in this scenario, including sugar maple (*Acer saccharum*), bigtooth aspen (*Populus grandidentata*), and yellow birch (*Betula alleghaniensis*). The same overall trends were evident in the regeneration data (see Supplemental Report S1). The NED-3 report also identified several species that are projected to have increased habitat under each scenario, including American basswood (*Tilia americana*), bitternut hickory (*Carya cordiformis*), and black cherry (*Prunus serotina*), which are all currently present in this stand. Habitats for American elm (*Ulmus americana*) and white ash (*Fraxinus americana*) are also projected to increase as a result of climate change, but these model results do not directly take into account likely future mortality from diseases or insect pests; this is where the Tree Atlas modification factors are also necessary to interpret the model outputs, which give low adaptability scores for these species. Otherwise, the portion of the stand "at risk" due to climate change may underreport, in both climate scenarios, the proportion of the stand that is actually under threat of decline.

Future management options prescribed by this plan and influenced by the consideration of climate risk place emphasis on increasing forest resilience compatible with aesthetic management. Managers identified management objectives to improve forest health, maintain larger tree sizes for a esthetics, and increase the proportion of species other than sugar maple over the long term. Changes in forest composition and structure are intended to occur over the long term using a variety of silvicultural techniques to encourage diverse regeneration, such as group selection, expanding gaps, or irregular harvests to favor the desired species. To diversify species composition, there will be a greater emphasis on establishing regeneration in future entries rather than relying on the regeneration that is currently present. Bitternut hickory was identified as one species to favor because it is projected to have large increases in habitat as a result of climate change, although the species is susceptible to periodic outbreaks of mortality from complex factors (Wisconsin Department of Natural Resources 2007). In the consideration of climate risk, managers also considered the potential to plant species that are currently not present on the site based on a combination of the Tree Atlas results and current site conditions, such as hackberry (*Celtis occidentalis*), black walnut (*Juglans nigra*), and white oak (*Quercus alba*).

Caroline Lake Property

The Caroline Lake Property is owned by The Nature Conservancy (TNC) and managed by Compass Land Consultants, Inc. (hereafter Compass). The 1,044-ac property, located in Iron Country in northern Wisconsin, is a working forest that has been managed for a variety of goals related to biodiversity and watershed protection since purchase from industrial ownership in 1997. The property is also a demonstration site for climate change adaptation (Janowiak et al. 2014b), and a new management plan was developed by Compass with explicit consideration of potential climate change impacts. Compass performed a complete forest inventory of the Caroline Lake Property in fall 2013 by repeating a robust forest inventory protocol developed by TNC and Compass on TNC's Two-Hearted River Forest Reserve in eastern Upper Michigan. Compass then created stand-level climate change reports within its proprietary Microsoft Excel-based forest inventory software (see Supplemental Report S2).

The climate-informed inventory data

S Supplementary data are available with this article at http://dx.doi.org/10.5849/jof.15-144.

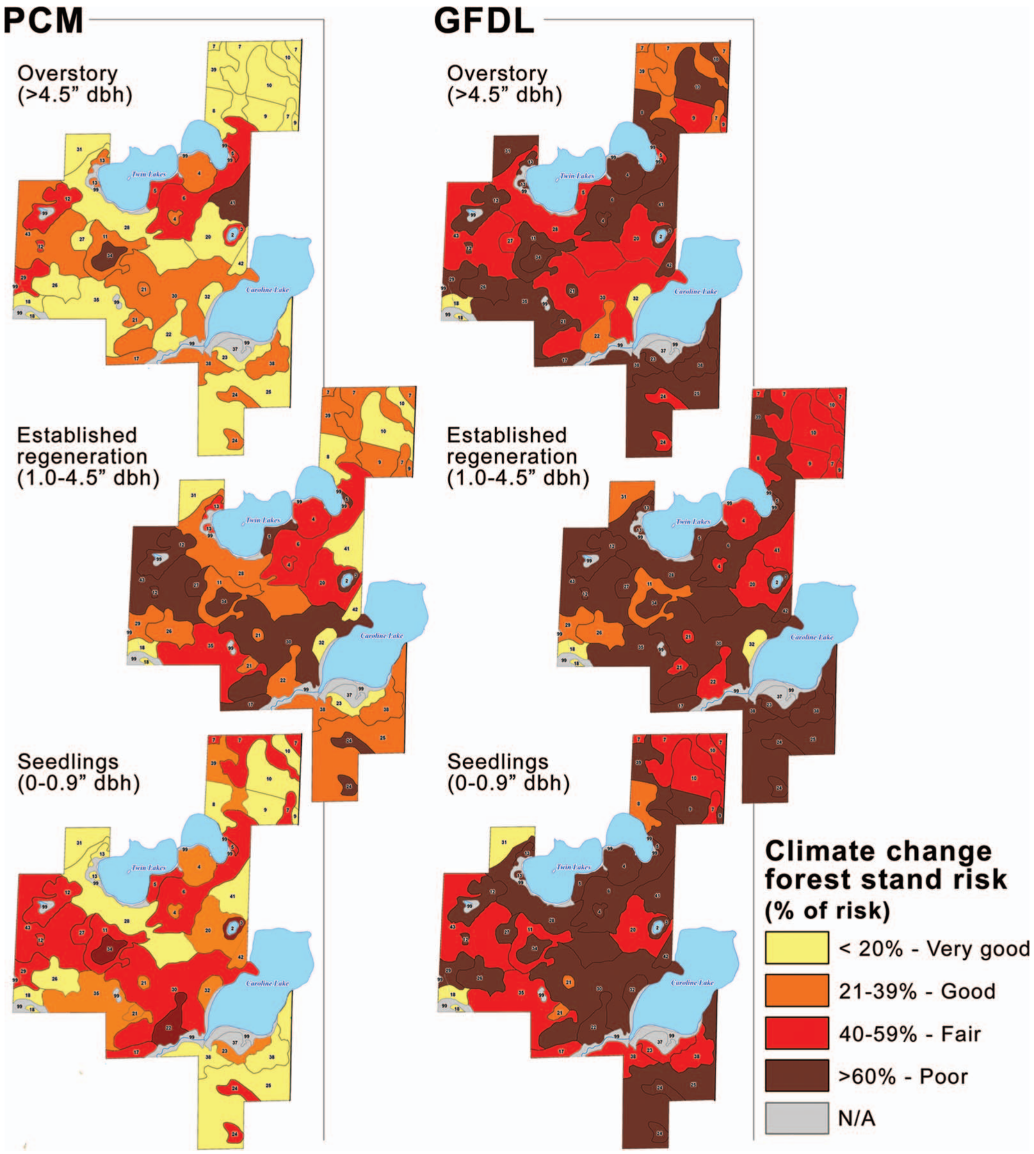

Figure 1. Mapped climate risk values for the Caroline Lake Property for trees (top), established regeneration (i.e., saplings; middle), and seedlings (bottom). Results are presented for two scenarios of climate change: a scenario of lesser climate change (PCM B1) and greater climate change (GFDL A1FI).

were used to inform a new management plan that was created for the property. The risk metric was applied for three different size classes of trees: overstory trees (>4.5 in. dbh), established regeneration (1.0–4.5 in. dbh), and seedlings (<1 in. dbh but >6 in. tall).

Climate risk for seedlings, established regeneration, and overstory trees was also mapped by stand and climate change scenario to illustrate trends in risk across the entire property (Figure 1). Under the scenario projecting less climate change (PCM B1), the stands with the highest proportion of species at risk were generally dominated by a few boreal species near the southern extent of their range in northern Wisconsin, including balsam fir (*Abies balsamea*), black spruce (*Picea mariana*), quaking aspen (*Populus tremuloides*), and tamarack (*Larix laricina*). In the conifer-dominated stands, the regeneration layer was often composed of similar species, resulting in higher levels of risk; in contrast, stands dominated by quaking aspen had lower risk in the understory under the PCM B1 scenario due to regeneration of less susceptible hardwood species.

The risk of species declines under climate change was much greater under the more severe scenario of climate change (GFDL A1FI) in trees as well as regeneration (Figure 1), because many of the most common hardwood species, including sugar maple, red maple (*Acer rubrum*), and bigtooth aspen are projected to decline in this scenario. A few species that are currently present are projected to have similar or increased habitat in the future, namely American basswood, black cherry, and northern red oak (*Quercus rubra*). At the same time, there are several factors that suggest the impacts of climate change may be less severe across the Caroline Lake Property than the Tree Atlas model results suggest under this scenario, again emphasizing the importance of also considering the Tree Atlas modification factors. Red maple, sugar maple, and northern red oak have numerous biological traits that indicate the species may fare better than the model suggests. Red maple, in particular, has the highest adaptability among all 134 species that have been modeled by the Tree Atlas (Matthews et al. 2011), and managers of the Caroline Lake Property believe that the species is well-poised to increase on the property in the future. In contrast to this, lowland conifer stands containing higher proportions of black ash (*Fraxinus nigra*) were generally calculated as having the lowest risk across the property using the risk metric, so the consideration of the modification factors and additional information help account for the potential for substantial losses from the emerald ash borer.

Given the consideration of climate change, the new management plan developed for the Caroline Lake Property placed an increased emphasis on maintaining and increasing tree species diversity, consistent with TNC's management goals, to reduce the potential for species declines to negatively affect the forest. The management plan identified several opportunities to promote species that are expected to be better adapted to future conditions, particularly in northern hardwood stands. Whereas past management primarily employed single-tree and small group selection, future management will increase the use of group selection, shelterwood, and other silvicultural practices that will increase natural regeneration of mid-tolerant species (Janowiak et al. 2014b). These species, such as northern red oak and black cherry, were projected to fare better in this area under future climate conditions and can be favored through management. A greater abundance of these species on the property would be expected to reduce the risk of decline from changing climate conditions and increase future management options. Further, the climate risk metrics could be used with future inventory data to evaluate whether management is effective in altering stand composition and reducing risk over time.

Summary

We have developed a climate risk metric that integrates data from forest inventories and species distribution models to aid forest managers in assessing how climate change may affect the areas that they manage. This approach uses projections of species change from the Climate Change Tree Atlas under different scenarios of climate change with basic, field-derived forest inventory data (Table 2). In doing this, we hope to bridge the divide that currently exists between regional-scale climate change-based forest modeling efforts and local management decisions. We have used the Tree Atlas in our example because it provides an accessible, transparent, and consistent data set for the entire eastern United States.

At-risk species are identified based on projected changes in habitat suitability at the end of the 21st century, which provides a starting point for managers to begin looking into the data. Managers are, however, expected to review the projections critically before deciding how they may affect their management. They are encouraged use information from the Tree Atlas website, including the modification factors, the reliability of the individual tree species models, and the list of tree species projected to increase to interpret the risk metric. Moreover, regional vulnerability assessments are also instrumental for gaining a fuller interpretation of anticipated change in forests in coming decades. Most importantly, managers are asked to draw on their expertise and knowledge of local site conditions to determine what components of the forest may be at greatest risk.

As the amount of climate change information continues to grow, it is important to recognize that the vast majority of information is still being produced at spatial scales greater than those used for management. By using forest inventory data to evaluate the applicability of regional climate data to local conditions, managers can draw on the strengths of each to inform management decisions.

Endnotes

1. For more information, see www.nrs.fs.fed.us/atlas.
2. For more information, see www.fs.fed.us/nrs/atlas/products/#ra.
3. For more information, see www.forestadaptation.org.
4. For more information, see www.nrs.fs.fed.us/tools/ned.

Literature Cited

Anderson, M.G., and C.E. Ferree. 2010. Conserving the stage: Climate change and the geophysical underpinnings of species diversity. *PLoS One* 5(7):e11554. doi:10.1371/journal.pone.0011554.

Avery, T.E., and H.E. Burkhart. 2015. *Forest measurements*, 5th ed. Waveland Press, Long Grove, IL. 456 p.

Brandt, L., H. He, L. Iverson, F.R. Thompson, P. Butler, S. Handler, M. Janowiak, et al. 2014. *Central hardwoods ecosystem vulnerability assessment and synthesis: A report from the central hardwoods climate change response framework project.* USDA Forest Service, Gen. Tech. Rep. NRS-124, Northern Research Station, Newtown Square, PA. 254 p. https://www.treesearch.fs.fed.us/pubs/45430.

Delworth, T.L., A.J. Broccoli, A. Rosati, R.J. Stouffer, V. Balaji, J.A. Beesley, W.F. Cooke, et al. 2006. GFDL's CM2 global coupled climate models. Part I: Formulation and simulation characteristics. *J. Climate* 19(5): 643–674. doi:10.1175/JCLI3629.1.

Fridley, J.D., J.P. Grime, A.P. Askew, B. Moser, and C.J. Stevens. 2011. Soil heterogeneity buffers community response to climate change in species-rich grassland. *Global Change Biol.* 17(5):2002–2011. doi:10.1111/j.1365-2486.2010.02347.x.

Glick, P., B.A. Stein, and N.A. Edelson. 2011. *Scanning the conservation horizon: A guide to climate change vulnerability assessment.* National Wildlife Federation, Washington, DC. 168 p.

Hannah, L., G.F. Midgley, and D. Millar. 2002. Climate change-integrated conservation strategies. *Global Ecol. Biogeogr.* 11(6):485–495. doi:10.1046/j.1466-822X.2002.00306.x.

Helms, J.A., ed. 1998. *The dictionary of forestry.* Society of American Foresters, Washington, DC. 210 p.

Holling, C.S. 1973. Resilience and stability of ecological systems. *Annu. Rev. Ecol. System.* 4: 1–23. doi:10.1146/annurev.es.04.110173.000245.

Iverson, L.R., A.M. Prasad, S.N. Matthews, and M. Peters. 2008. Estimating potential habitat for 134 eastern us tree species under six climate scenarios. *For. Ecol. Manage.* 254(3): 390–406. doi:10.1016/j.foreco.2007.07.023.

Janowiak, M.K., L. Iverson, D.J. Mladenoff, E. Peters, K.R. Wythers, W. Xi, L.A. Brandt, et al. 2014a. *Forest ecosystem vulnerability assessment and synthesis for northern Wisconsin and western upper Michigan: A report from the Northwoods Climate Change Response Framework.* USDA Forest Service, Gen. Tech. Rep. NRS-136, Northern Research Station, Newtown Square, PA. 247 p. https://www.treesearch.fs.fed.us/pubs/46393.

Janowiak, M.K., C.W. Swanston, L.M. Nagel, L.A. Brandt, P.R. Butler, P.D. Shannon, L.R. Iverson, S.N. Matthews, A. Prasad, and M.P. Peters. 2014b. A practical approach for translating climate change adaptation principles into forest management actions. *J. For.* 112(5):424–433. doi:10.5849/jof.13-094.

Joyce, L.A., G.M. Blate, J.S. Littell, S.G. McNulty, C.I. Millar, S.C. Moser, R.P. Neilson, K. O'Halloran, and D.L. Peterson. 2008. National forests. P. 3-1 to 3-127 in *Preliminary review of adaptation options for climate-sensitive ecosystems and resources. A report by the US climate change science program and the subcommittee on global change research*, Julius, S.H., and J.M. West (eds.). US Environmental Protection Agency, Washington, DC.

Landscape Change Research Group. 2015. *Climate change atlas.* USDA Forest Service, Northern Research Station, Delaware, OH. https://www.fs.fed.us/nrs/atlas/.

Matthews, S.N., L.R. Iverson, A.M. Prasad, M.P. Peters, and P.G. Rodewald. 2011. Modifying climate change habitat models using tree species-specific assessments of model uncertainty and life history-factors. *For. Ecol.*

Manage. 262(8):1460–1472. doi:10.1016/j.foreco.2011.06.047.

Nakicenovic, N., and R. Swart. 2000. Special report on emissions scenarios. *Special report on emissions scenarios*, Nakicenovic, N., and R. Swart. Cambridge University Press, Cambridge, UK. 612 p.

Pearson, R.G., and T.P. Dawson. 2003. Predicting the impacts of climate change on the distribution of species: Are bioclimate envelope models useful? *Global Ecol. Biogeogr.* 12(5):361–371. doi:10.1046/j.1466-822X.2003.00042.x.

Peters, G.P., R.M. Andrew, T. Boden, J.G. Canadell, P. Ciais, C. Le Quéré, G. Marland, M.R. Raupach, and C. Wilson. 2013. The challenge to keep global warming below 2 c. *Nat. Climate Change* 3(1):4–6. doi:10.1038/nclimate1783.

Peterson, D.L., C.I. Millar, L.A. Joyce, M.J. Furniss, J.E. Halofsky, R.P. Neilson, and T.L. Morelli. 2011. *Responding to climate change on national forests: A guidebook for developing adaptation options.* USDA Forest Service, Gen. Tech. Rep. PNW-GTR-855, Pacific Northwest Research Station, Portland, OR. 109 p. https://www.treesearch.fs.fed.us/pubs/39884.

Prasad, A.M., L.R. Iverson, and A. Liaw. 2006. Newer classification and regression tree techniques: Bagging and random forests for ecological prediction. *Ecosystems* 9(2):181–199. doi:10.1007/s10021-005-0054-1.

Rowland, E., and M. Cross. 2015. *Monitoring & evaluation in climate change adaptation projects: Highlights for conservation practitioners.* Wildlife Conservation Society, New York. 10 p.

Schneiderman, J.E., H.S. He, F.R. Thompson, W.D. Dijak, and J.S. Fraser. 2015. Comparison of a species distribution model and a process model from a hierarchical perspective to quantify effects of projected climate change on tree species. *Landsc. Ecol.* 30(10):1879–1892. doi:10.1007/s10980-015-0217-1.

Stein, B.A., P. Glick, N. Edelson, and A. Staudt (eds.). 2014. *Climate-smart conservation: Putting adaptation principles into practice.* National Wildlife Federation, Merrifield, VA. 262 p.

Swanston, C.W., M.K. Janowiak, L.A. Brandt, P.R. Butler, S.D. Handler, P.D. Shannon, A. Derby Lewis, et al. 2016. *Forest adaptation resources: Climate change tools and approaches for land managers, 2nd ed.* U.S. Department of Agriculture, Forest Service. Gen. Tech. Rep. NRS-87-2, Northern Research Station, Newtown Square, PA. 161 p. https://www.treesearch.fs.fed.us/pubs/52760.

Washington, W.M., J.W. Weatherly, G.A. Meehl, A.J. Semtner, Jr., T.W. Bettge, A.P. Craig, W.G. Strand Jr., J. Arblaster, V.B. Wayland, R. James, and Y. Zhang. 2000. Parallel climate model (PCM) control and transient simulations. *Climate Dyn.* 16(10):755–774. doi:10.1007/s003820000079.

Wiens, J.A., D. Stralberg, D. Jongsomjit, C.A. Howell, and M.A. Snyder. 2009. Niches, models, and climate change: Assessing the assumptions and uncertainties. *Proc. Natl. Acad. Sci. U.S.A.* 106(Suppl. 2):19729–19736. doi:10.1073/pnas.0901639106.

Wisconsin Department of Natural Resources. 2007. *Hickory dieback and mortality in Wisconsin.* Wisconsin Department of Natural Resources, Forest Health Protection. Available online at dnr.wi.gov/topic/ForestHealth/documents/HickoryMortalityFactsheet.pdf; last accessed Feb. 8, 2017.